공학석사학위논문

Joint Relay Selection and Resource Allocation for Network Coding-based Video Multicast in WLAN

무선 LAN에서 네트워크 코딩 기반의 비디오 멀티캐스트를 위한 릴레이 선택 및 자원 할당 기법

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Abstract

This thesis presents a joint relay selection and resource allocation algorithm for network coding based video multicast in wireless local area networks (WLANs). Multicast is an effective solution to transmit real-time video data to a group of multiple nodes simultaneously. However, according to IEEE 802.11 WLAN standards, multicast does not guarantee reliability for packet delivery because no retransmission is regulated to deal with lost packets. To get over this limitation, the thesis considers random linear network coding (RLNC) which enables reliable transmission even when a part of transmitted packets are lost. In addition, it considers two-hop transmission using relays as it is more bandwidth-effective than one-hop transmission. Taking advantage of the benefits of the RLNC and the relaying, the thesis formulates an optimization problem with the objectives of maximizing the number of nodes which receive reliable video packets and minimizing the number of total transmitted packets from the sender nodes. The formulated problem is not convex but it is possible to modify it to a linear programming (LP) problem aiming at minimizing the number of total transmitted packets by constraint relaxation. As a consequence the thesis presents a heuristic algorithm based on the LP. According to numerical simulations, the proposed algorithm performs close to the optimal scheme and outperforms the existing scheme in terms of the number of decodable nodes and air time usage.

Keywords: Video multicast, random linear network coding, relay.

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Chapter 1

Introduction

As smart mobile devices such as smart phones and tablet PCs get widely spread, demands for applications for real−time video streaming over wireless networks have proliferated. Wireless multicast, which has wireless broadcast nature, has been known as an effective solution to providing real−time video to multiple nodes simultaneously. However, each node receiving a multicast transmission suffers from different packet loss due to variation of the wireless channels. Furthermore, according to IEEE 802.11 WLAN standards, multicast does not guarantee the reliability for packet delivery because no retransmission is regulated to deal with lost packets [1].

The random linear network coding (RLNC) may possibly render a useful means to overcoming the above challenges: Even though each node goes through a different packet loss, RLNC enables decoding the original packets only if each node receives enough number of encoded packets needed for decoding. In addition, if the receiver nodes which successfully decode the original packets transmit the received packets again, it will assist packet reception of the nodes far away from the source. Such multi-hop relaying is more bandwidth effective than the single-hop transmission as it reduces the total number of transmitted packets.

There are several papers that studied relay and network coding to develop efficient multicast schemes. In [2], the authors proposed a scheme for video transmission using network coding based two-hop relay. They formulated an optimization problem to maximize the total throughput by selecting the relays and scheduling the transmission time to the selected relays. However, the throughput maximization does not guarantee the quality of service (QoS) of each node. In [3], the authors developed a relay and bit-rate selection algorithm called UFlood for flooding the overall data to all the nodes through network coding based multi-hop relay in a mesh network. The UFlood selects the relay and its bit-rate based on the delivery probabilities and feedback which includes the reception status of each node. In [4], the authors presented the MNP scheme which selects relays for transmitting the entire data with multi-hop in sensor networks. In the MNP, a source node multicasts the original packets to neighbor nodes, and the neighbor node which receives the whole packets multicasts the packets to its neighbor nodes. The MNP selects the relay which has the largest number of neighbor nodes. However, the schemes in [3] and [4] both permit retransmission to successfully transmit the packets and, thus, are not suitable for delay-sensitive real-time video transmission.

This thesis intends to present a joint relay selection and resource allocation algorithm for RLNC-based video multicast. The main objective of the algorithm is to maximize the number of nodes which receive reliable video packets for guaranteeing the QoS. It also has a sub-objective of minimizing the number of total transmitted packets to reduce air time usage and thus utilize bandwidth efficiently. An optimization problem will be formulated to determine the relays and resource allocation for simultaneously achieving above two objectives. However, as the problem turns out to be non-convex, a linear programming (LP) problem will be sought for by relaxing the constraints, which will yield heuristic algorithms for determining the relays and allocated resources.

This thesis is organized as follows. Chapter 2 introduces the system model of considered multicast model and assumptions. Then Chapter 3 formulates the optimization problem and Chapter 4 reformulates an LP problem and presents heuristic algorithms. Chapter 5 reports simulation results and discusses the performance of the proposed algorithm. Finally, Chapter 6 concludes the thesis.

Chapter 2

System Model

We consider an ad hoc network in which a multicast group consists of one source and multiple receivers. We take into account network coding based two−hop multicast transmission. The source multicasts video packets by using RLNC, and some of receivers forward the packet after encoding them again.

RLNC is used for the reliable multicast, which facilitates decoding original packets at the receivers even if they have lost different parts of transmitted packets. If K original packets are $n_1, n_2, ..., n_K$, $e = \sum_{i=1}^{K} c_i n_i$ where e is a linear combination of K original packets and $c_1, c_2, ..., c_K$ are randomly chosen integer coefficients in the Galois field $GF(2^8)$. Each encoded packet which includes coefficients $c_1, c_2, ..., c_K$ and linear combination e is generated by the source. When the source transmits

N encoded packets, i.e., generates $(N-K)$ additional packets, each receiver can decode the original packets by the Gaussian elimination if it receives K or more linearly independent encoded packets.

We define one−hop nodes as the receivers which can successfully decode the original packets by using packets received only from the source. In addition, they become relay candidates, which are willing to forward the packets. The one−hop nodes multicast packets encoded over the decoded original packets which they have received from the source. In contrast, we define two−hop nodes as the nodes which cannot decode the packets received from the source at once. The two−hop nodes can decode the original packets when they receive more than or equal to K linearly independent packets in total from individual senders, i.e., the source and the relays.

In RLNC−based packet transmission, it is important to predict the number of received packets at each receiver when the sender multicasts encoded packets. The probability that a node receives x packets when the sender transmits N packets through the link with the packet delivery ratio (PDR) p takes the form of a binomial probability mass function (PMF) as follows.

$$P(X=x)=\binom{N}{x} p^{x}\,(1-p)^{N-x}. \tag{2.1}$$

From (2.1), if the sender transmits N packets, the expected number

K^* of received packets with a probability higher than p_{thre} is derived from binomial cumulative density function (CDF) as follows.

$$\begin{aligned} K^* &= \max\left\{x \mid P(X \geq x) \geq p_{thre}\right\} \\ &= \max\left\{x \mid \sum_{i=x}^{N} P(X = i) \geq p_{thre}\right\}. \end{aligned} \tag{2.2}$$

However, it is too complex to calculate the expected number of received packets for all the links by using (2.2). Thus, in order to simply estimate the number of delivered packets, we adapt the metric proposed in [5]. The metric is obtained by approximating (2.2) in polynomial forms and it takes the expression

$$\tilde{K} = \alpha N p^2, \tag{2.3}$$

where $\tilde{K}$ denotes the expected number of received packets when the sender transmits N packets for a given PDR p and α denotes the weight parameter depending on p_{thre}. There is no observable video quality degradation when the decoding failure rate is equal or below 0.5% [6]. Therefore, we set α to 0.7233 where the decoding success rate threshold p_{thre} is 99.5% [5]. Inversely, we can expect how many packets the sender has to transmit for allowed each receiver to receive $\tilde{K}$ packets with a target reliability by using (2.3).

The target application is to transmit the video packets in real-time. The video has to be played back sustainably for satisfying the QoS of

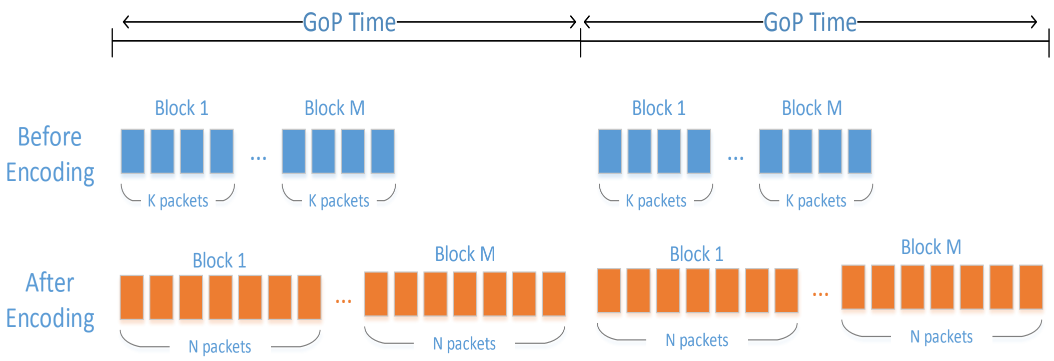

Fig. 1. An example of video packet transmission.

each user. In such a delay sensitive video transmission, the video packet transmission time should be faster than play back time, so that the maximum number of total transmitted packet at the source and relay nodes is limited to given time.

Fig. 1 depicts an example of video packet transmission. Each video frame composes each group of pictures (GoP), which is a basic unit of video processing. In the source, original packets generated from a GoP are grouped into M blocks, and each block contains K original packets. After encoding K original packets in each block by using the RLNC, the source generates N encoded packets and each of them has the same length. Then, M blocks should be transmitted within a GoP time to prevent the transmitted packets in a current GoP from affecting the transmission of the next GoP. Thus, the maximum number $N_{\max}$ of transmitted packets for a block is bounded as follows.

$$N_{\max} \leq \frac{\text{GoP Time}}{M \cdot T_L}, \text{ where } \quad T_L = \frac{L_{PHY}}{R_{PHY}} + \text{overhead.} \qquad (2.4)$$

T_L indicates the packet transmission time when an encoded packet with the length of L_{PHY} is transmitted at a fixed rate R_{PHY} at PHY layer. GoP time is a given transmission time for a GoP.

This system relies on the following assumptions. Each node has a radio that operates at a fixed power level and modulation and coding scheme (MCS), on a single wireless channel, and PHY overhead is negligible. In addition, all the encoded packets generated by using the RLNC are linearly independent. Nodes are stationary and PDRs for each link are measured in initial training session. The transmission of each sender is scheduled in different time.

Chapter 3

Problem Statement

This chapter presents an optimization problem which jointly selects the relays and determines the number of packets the source and each relay will transmit. This problem is based on the system model in the previous chapter. We consider the situation in which L receivers exist. Initially, the source s transmits N_s encoded packets generated out of K original packets from a block. If node k receives K packets only from the source, it can relay N_k re−coded packets. If $N_k > 0$, node k operates as a relay, otherwise, node k operates as a receiver only.

Our main objective is to maximize the number of decodable nodes for meeting the QoS of each node k. The sub−objective is to minimize the number of transmitted packets for improving the bandwidth efficiency. The optimization problem which considers two objectives with different priorities can be formulated as follows.

$$\underset{m_1,\ldots,m_L,N_s,N_1,\ldots,N_L}{\text{maximize}} \quad \sum_{k=1}^{L} m_k + \frac{N_{\max} - \left(N_s + \sum_{k=1}^{L} N_k\right)}{N_{\max}} \tag{3.1a}$$

$$\text{subject to} \quad N_s \geq 0;\ N_k \geq 0, \forall k \tag{3.1b}$$

$$N_s + \sum_{k=1}^{L} N_k \leq N_{\max} \tag{3.1c}$$

$$\left(\alpha N_s p_{s,k}^2 - K\right) N_k \geq 0, \forall k \tag{3.1d}$$

$$\left\lfloor \alpha N_s p_{s,l}^2 \right\rfloor + \sum_{k=1,k\neq l}^{L} \left\lfloor \alpha N_k p_{k,l}^2 \right\rfloor \geq K m_l, \forall l, \tag{3.1e}$$

where l indicates the dummy index of node k. $m_k \in \{0,1\}$ denotes the decodable node indicator either node k can decode the original packets or not, i.e., if node k receives more than or equal to K packets in transmissions, $m_k = 1$. Otherwise, node k is excluded for the reliable transmission, and $m_k = 0$. $N_{\max}$ indicates the maximum number of total transmitted packets, which is determined by the GoP time. α denotes the weight parameter for (2.3) and $p_{a,b}$ is the PDR of link from node a to node b.

In the objective function (3.1a), $\sum_{k=1}^{L} m_k$ is a non-negative integer value which indicates the number of decodable nodes. The term $N_s + \sum_{k=1}^{L} N_k$ is the total number of packets transmitted from nodes, which is subtracted and normalized by $N_{\max}$ in (3.1a). Thus, maximizing

$\left\{N_{\max}-\left(N_s+\sum_{k=1}^{L}N_k\right)\right\}/N_{\max}$ is equivalent to minimize the number of total transmitted packets. Since the first part of the objective function always has integer value and the second part of that has the real value in the range of $[0,1]$, the first part takes higher priority over the second part, and thus, we preferentially maximize the number of decodable nodes. In this thesis, the objective function (3.1a) is called the utility.

(3.1b) represents that the number of packets transmitted from each node is non-negative. Constraint (3.1c) bounds the total number of packets transmitted from all senders up to $N_{\max}$. (3.1d) determines the one-hop nodes and two-hop nodes. If node k received more than K packets only from the source, i.e., $\alpha N_s p_{s,k}^2 - K \ge 0$, it is the one-hop node. Then, it can multicast non-negative integer packets and it is included in relay candidate, which means $N_k \ge 0$ from (3.1b). In contrast, if $\alpha N_s p_{s,k}^2 - K < 0$, node k becomes the two-hop node. In other words, it does not forward the packets, i.e., $N_k = 0$ by (3.1b). Constraint (3.1e) represents that the decodable nodes should receive more than or equal to K packets which is the sum of the packets from the individual nodes. In (3.1e), the floor operation is used to express that we expect the integer number of packets received from each node with a high reliability.

It turns out that the above problem is an integer programming problem, since it involves integer variables. Thus, the problem is non-convex because it does not contain a convex set. Such kind of problem is generally very difficult to solve [7]. Therefore, we propose an algorithm to make this problem tractable in the next chapter.

Chapter 4

Relay Selection and Resource Allocation Algorithm

In this chapter, we propose an algorithm to select the relays and to allocate the resources by relaxing the optimization problem. First, we assume that all the nodes are able to decode the original packets, i.e., $m_k = 1, \forall k \in \{1, \ldots, L\}$, without considering $N_{\max}$ at the beginning. In such a case, the problem can be modified into a problem to minimize the total transmitted packets. If N_s is a fixed value, we can classify nodes into the one−hop nodes and the two−hop nodes by using (2.3). We relax the integer variables to the real values in order to make the problem tractable. In such considerations, we reformulate a problem as a linear programming (LP) problem. Then, we can determine the relays and allocated resources by using an optimal solution of LP. From this point of view, we propose an algorithm which can find the suboptimal solution of (3.1).

The overall operation of the proposed algorithm is described in Algorithm 1. The remaining part of this chapter will explain the process of the algorithm in detail.

4.1 Resource Allocation for the Source

We determine the range of the number of packets transmitted from the source in order to fix N_s for modifying the problem (3.1) to the convex problem. The source should transmit the packets as at least one node can decode the original packets for relaying. Thus, the minimum number of packets transmitted from the source is calculated by considering the node which has the best link quality with the source as follows.

$$N_{s,\min} = \left\lceil \frac{K}{\alpha \cdot \max(p_{s,k}^2)} \right\rceil. \tag{4.1}$$

In (4.1), the ceiling operator is used to make the real value of an inner term to the integer value. It is obvious that the number of packets has the integer value and the receiver node receives more than K packets reliably.

Algorithm 1 Relay selection and resource allocation algorithm

Initialize $N_k = 0, k \in \{1,...,L\}; x = 1,\ excluded\_nodes = 0$;
while $x > 0$ **do**
    Initialize $\tilde{N}_s = N_{\max}, \tilde{N}_k = N_{\max}, \forall k \in \{1,...,L\}$;
    Calculate $N_{s,\min}, N_{s,\max}$ from (4.1) and (4.2);
    for $N_s = N_{s,\min}$ to $N_{s,\max}$ **do**
        Initialize $\mathbb{O} = \varnothing,\ \mathbb{T} = \varnothing$;
        if $\alpha N_s p_{s,k}^2 \geq K,\ \forall k \in \{1,...,L\}$
            $\mathbb{O} = \mathbb{O} \bigcup \{k\}$;
        else
            $\mathbb{T} = \mathbb{T} \bigcup \{k\}$;
        end if
        $count = excluded\_nodes$;
        while $count > 0$ **do**
            Select the excluded node $j^* \in \mathbb{T}$ by (4.4), (4.5) or (4.6);
            $\mathbb{T} = \mathbb{T} \backslash \{j^*\}$;
            $count = count - 1$;
        end while
        Select relays and calculate the allocated resources N_i based on (4.3);
        Perform Algorithm 2 to transform the real values of LP into the integer;
        if $N_s + \sum_i N_i < \tilde{N}_s + \sum_i \tilde{N}_i$
            $\tilde{N}_k = 0, \forall k \in \{1,...,L\}$;
            $\tilde{N}_s = N_s, \tilde{N}_i = N_i, \forall i \in \mathbb{O}$;
        end if
    end for
    if $\tilde{N}_s + \sum_i \tilde{N}_i \leq N_{\max}$ **do**
        $x = 0$;
    else
        $excluded\_nodes = excluded\_nodes + 1$;
    end if
end while
Update $N_s = \tilde{N}_s, N_i = \tilde{N}_i, \forall i \in \mathbb{O}$;
Allocate the resources N_s to the source and N_i to the relays $i \in \mathbb{O}$;

The maximum number of packets transmitted from the source take into account the node which has the worst link quality with the source, i.e., the source transmits the packets to all nodes as the single-hop transmission. However, this cannot exceed $N_{\max}$ by constraint (3.1c).

$$N_{s,\max} = \min\left(\left\lceil \frac{K}{\alpha \cdot \min(p_{s,k}^2)} \right\rceil, N_{\max}\right). \tag{4.2}$$

From (4.1) and (4.2), N_s is incremented one by one from $N_{s,\min}$ to $N_{s,\max}$. At each fixed N_s, we can allocate the resources to the nodes by using the modified problem as will be described in the next section.

4.2 Relay Selection and Resource Allocation

At a fixed N_s, now we can categorize the nodes into the one-hop nodes and the two-hop nodes by using (2.3) since α, N_s, $p_{s,k}$ and K are given parameters. If $\alpha N_s p_{s,k}^2 \geq K$, node k belongs to the one-hop nodes set $\mathbb{O}$. Otherwise, node k belongs to the two-hop nodes set $\mathbb{T}$ which should receive more packets from the one-hop nodes for decoding the packets successfully.

It is clear that the one-hop nodes are relay candidates. Thus, we do not require the constraint (3.1d) any more. Initially, we exclude the time constraint (3.1c) and the integer values are relaxed to the real values. With taking into account such conditions, we can reformulate the problem to minimize the total number of transmitted packets by the relays as follows.

$$\underset{N_i, \forall i \in \mathbb{O}}{\text{minimize}} \quad \sum_{i \in \mathbb{O}} N_i \tag{4.3a}$$

$$\text{subject to} \quad N_i \geq 0, \forall i \in \mathbb{O} \tag{4.3b}$$

$$\alpha N_s p_{s,j}^2 + \sum_{i \in \mathbb{O}} \alpha N_i p_{i,j}^2 \geq K, \forall j \in \mathbb{T}, \tag{4.3c}$$

where $i \in \mathbb{O}$ denotes the index of the one−hop node, and $j \in \mathbb{T}$ is the index of the two−hop node. (4.3b) substitutes for the (3.1b), which considers the number of packets transmitted just from the relay candidates. (4.3c) means that the two−hop nodes should receive more than K packets from senders, which substitutes for the constraint (3.1e) in real value form.

The formulated problem (4.3) is an LP problem. It is obvious that the problem is feasible and bounded, and therefore a unique optimal solution exists [8]. We can obtain the number of packets transmitted from each relays from the optimal variables of (4.3).

However, the optimal variables have the real values and (4.3c) does not guarantee that the two−hop node receives the integer valued packets from each link. Thus, we propose an algorithm to transform them into the proper integer values since the number of packets always has an integer value. Algorithm 2 illustrates the process to find the proper integer number of packets transmitted by each relay.

In Algorithm 2, the real values of LP are applied to the floor operation to prevent the excessive number of packets from transmitting at each relays and to make them integer values. With considering the optimization problem (3.1), we check two-hop nodes $j \in \mathbb{T}$ to satisfy the constraint (3.1e). If two-hop node j does not meet the constraint, the node belongs to the set $\mathbb{A}$ which requires more packets to decode the original packets. In the subsequent processes, the algorithm is operated iteratively until two-hop node $j \in \mathbb{A}$ meets the constraint (3.1e). The number of packets transmitted from each relay is incremented one by one. When any node $j \in \mathbb{A}$ receives additional packets from relay i, we define that the relay node yields a gain $G_{i,j}$. The number of packets transmitted from a relay which yields the highest gain replaces the old value. From the updated number of transmitted packets, the node which satisfies the constraint (3.1e) is excluded for set $\mathbb{A}$. The algorithm is terminated when set $\mathbb{A}$ gets empty.

In this way, we can determine the integer number of packets transmitted from each relay which meets the feasible set for LP problem (4.3). Then, we compute the total number of transmitted packets for all

Algorithm 2 Transformation the real values into the integer

Initialize $N_i^* = \lfloor N_i \rfloor, \forall i \in \mathbb{O}; y = 1, \ \mathbb{A} = \varnothing;$

for $j \in \mathbb{T}$ **do**

  if $\lfloor \alpha N_s p_{s,j}^2 \rfloor + \sum_{i \in \mathbb{O}} \lfloor \alpha N_i^* p_{i,j}^2 \rfloor < K$ **then**

    $\mathbb{A} = \mathbb{A} \bigcup \{j\};$

  end if

end for

while $\mathbb{A} \neq \varnothing$ **do**

  for $i \in \mathbb{O}$ **do**

    for $j \in \mathbb{A}$ **do**

      $G_{i,j} = \left\lfloor \alpha \left(N_i^* + y \right) p_{i,j}^2 \right\rfloor - \left\lfloor \alpha \left(N_i^* + y - 1 \right) p_{i,j}^2 \right\rfloor;$

    end for

  end for

  if any $G_{i,j} > 0$ **then**

    $i^* = \arg\max_i \sum_{j \in \mathbb{A}} G_{i,j};$

    $N_{i^*}^* = N_{i^*}^* + y;$

    $y = 1;$

    for $j \in \mathbb{A}$ **do**

      if $\lfloor \alpha N_s p_{s,j}^2 \rfloor + \sum_{i \in \mathbb{O}} \lfloor \alpha N_i^* p_{i,j}^2 \rfloor \geq K$ **then**

        $\mathbb{A} = \mathbb{A} \setminus \{j\};$

      end if

    end for

  else

    $y = y + 1;$

  end if

end while

Update $N_i = N_i^*, \forall i;$

N_s. It is an solution to satisfy the given node set when we obtain the minimum number of total transmitted packets at the specific N_s and we update the allocated resources $\tilde{N}_s$ to the source and $\tilde{N}_i$ to the relays.

4.3 Node Exclusion

We can get the solution for the minimum total number of transmitted packets in order to satisfy the reliable packet receptions for the given node set in previous sections. If $\tilde{N}_s + \sum_i \tilde{N}_i \le N_{\max}$, the constraint (3.1c) is satisfied and there exists the solution of the (3.1). However, if $\tilde{N}_s + \sum_i \tilde{N}_i > N_{\max}$, the solution does not guarantee (3.1c). In such a case, the solution which meets the constraints in (3.1) for the node set does not exist. Thus, we should find an optimal node set in order to meet the constraints. In other words, we should exclude some nodes in the node set for the reliable transmission since too many packets are transmitted in order to satisfy all the nodes. However, it is too complex to find the optimal node set because we should consider all the outcomes of node set.

Therefore, we propose three heuristic metrics to exclude an appropriate node which requires relatively many packets for decoding the original packets.

$$\text{Metric 1: } j^* = \arg\min_j p_{s,j}, \forall j \in \mathbb{T} \tag{4.4}$$

Metric 1 chooses the excluded node as a node which has the worst PDR from the source. It considers a situation where the node requires too many packets transmitted from the source at the single-hop transmission.

$$\text{Metric 2: } j^* = \arg\min_j \max_i p_{i,j}, \forall j \in \mathbb{T} \tag{4.5}$$

In two-hop transmission, two-hop nodes highly rely on the transmission from the best relay with oneself. In this manner, Metric 2 excludes a node which has the worst PDR with the best relay.

$$\text{Metric 3: } j^* = \arg\min_j \left(p_{s,j}^2 + \sum_i p_{i,j}^2 \right), \forall j \in \mathbb{T} \tag{4.6}$$

Metric 3 excludes the node which has the smallest expected number of packets received from all the senders when they multicast the same number of packets. In (4.6), p^2 is from the (2.3).

We exclude the node one by one in the node set by using a metric among the three proposed heuristic metrics. We compute iteratively the allocated resources on each node set until $\tilde{N}_s + \sum_i \tilde{N}_i \le N_{\max}$. At that time, we can determine the relay set and the allocated resources to achieve the objective function (3.1a).

Chapter 5

Performance Evaluation

In this chapter, we conduct simulations to verify the performance of the proposed algorithms. For the simulations, the nodes of the ad hoc multicast group are randomly distributed on a squared topology. For WLAN, each node is equipped with the radio which operates at 20 dBm transmit power and with the transmission rate of 24 Mbps, and the noise power is −92 dBm. Each node experiences the channel which is modeled according to IEEE 802.11 channel model [9]. We assume that the GoP time is 0.5 sec and the number of blocks M in a GoP is 10. From such assumptions, when we set the packet length to 1500 bytes and the number of original packets K in a block to 10, the maximum number of transmitted packets $N_{\max}$ for a block is set to 100 by (2.4). Initially, the PDRs are measured by transmitting the 1000 packets at each node for performing the algorithm. The relay selection and the resource allocation

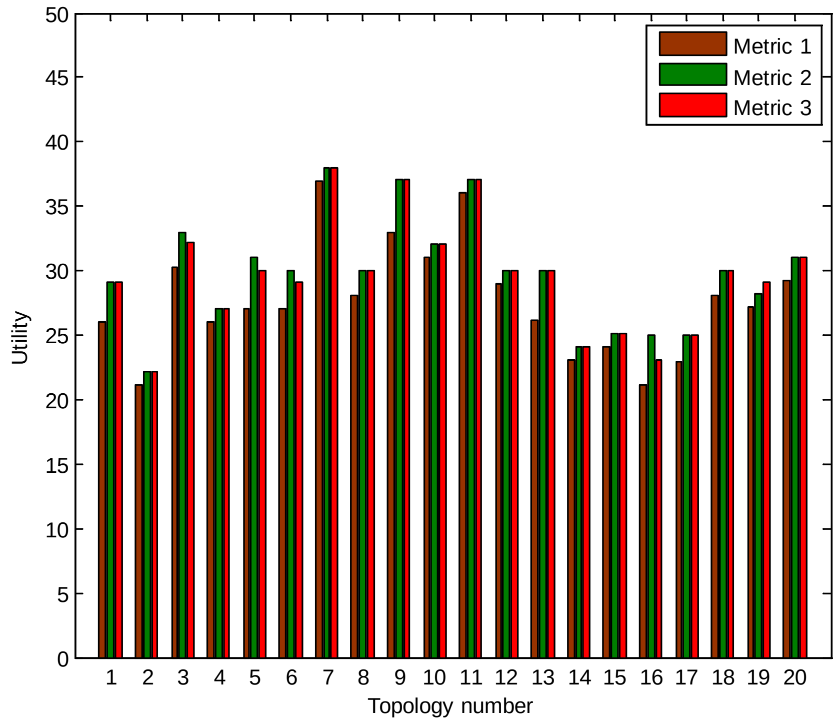

Fig. 2. Performance comparison of the proposed algorithms.

are computed by using the proposed algorithm based on initial PDRs.

Fig. 2 depicts the performances of the three proposed algorithms by using each heuristic metric, i.e., Metric 1 (4.4), Metric 2 (4.5), and Metric 3 (4.6), respectively. In this simulation, 40 nodes are randomly distributed on each topology. Note that the utility is the objective function (3.1a), i.e., $\text{Utility} = \sum_{k=1}^{L} m_k + \left\{ N_{\max} - \left(N_s + \sum_{k=1}^{L} N_k \right) \right\} / N_{\max}$.

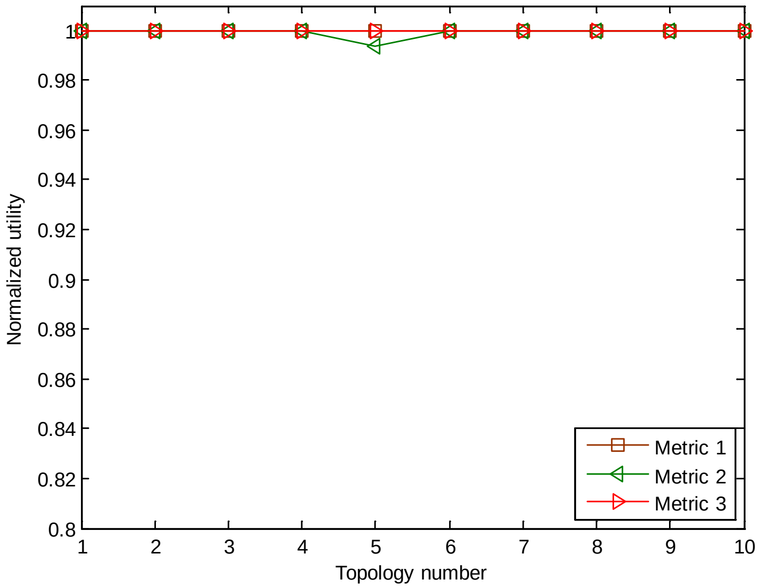

Fig. 3. Normalized utility when the number of the nodes is 10.

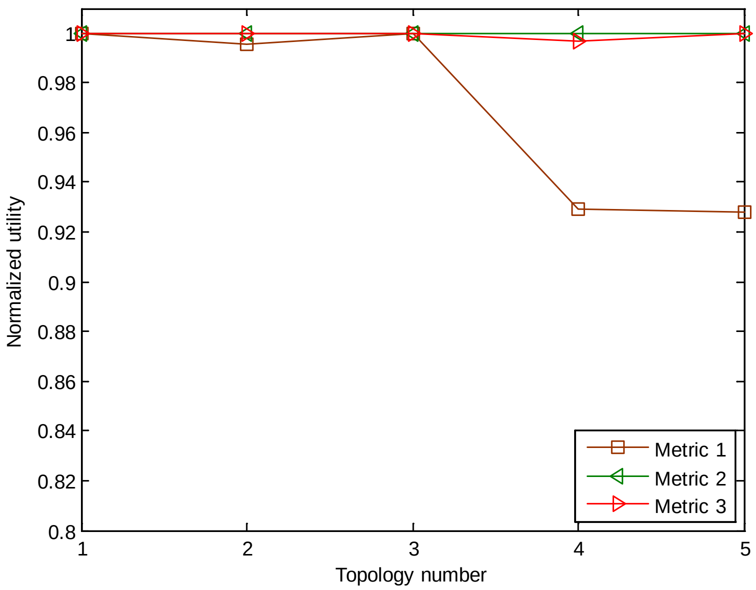

Fig. 4. Normalized utility when the number of the nodes is 20.

We observe that the utilities of the algorithms using Metric 2 and Metric 3 are always higher than that using Metric 1 on the all topologies. This occurs because Metric 2 and Metric 3 exclude the nodes based on the two−hop relay multicast, whereas Metric 1 excludes the node based on the single−hop transmission. The performance of Metric 2 is almost similar to that of Metric 3 for the most topologies.

Next, we examine how close the solution by the proposed algorithms is to the optimal solution which is obtained by an exhaustive search. Figs. 3 and 4 depict the normalized utility which is the utility of proposed algorithm over that of the optimal solution. In Fig. 3, we observe that all the utilities of the proposed algorithms approach nearly 1, i.e., the solution of the proposed algorithms is almost the same as the optimal solution. We also observe that the utilities of the proposed algorithms using Metric 2 and Metric 3 are very close to the optimal utility in Fig. 4. However, the normalized utility of the proposed algorithm using Metric 1 is relatively low in several topologies since Metric 1 excludes the nodes which are able to receive the packets with satisfying the constraints (3.1). Nevertheless, we observe that the solution obtained by using Metric 1 is also close to the optimal solution since the normalized utilities of Metric 1 are higher than 0.9. Therefore, we turned out that the proposed algorithms nearly approach to the optimal solution.

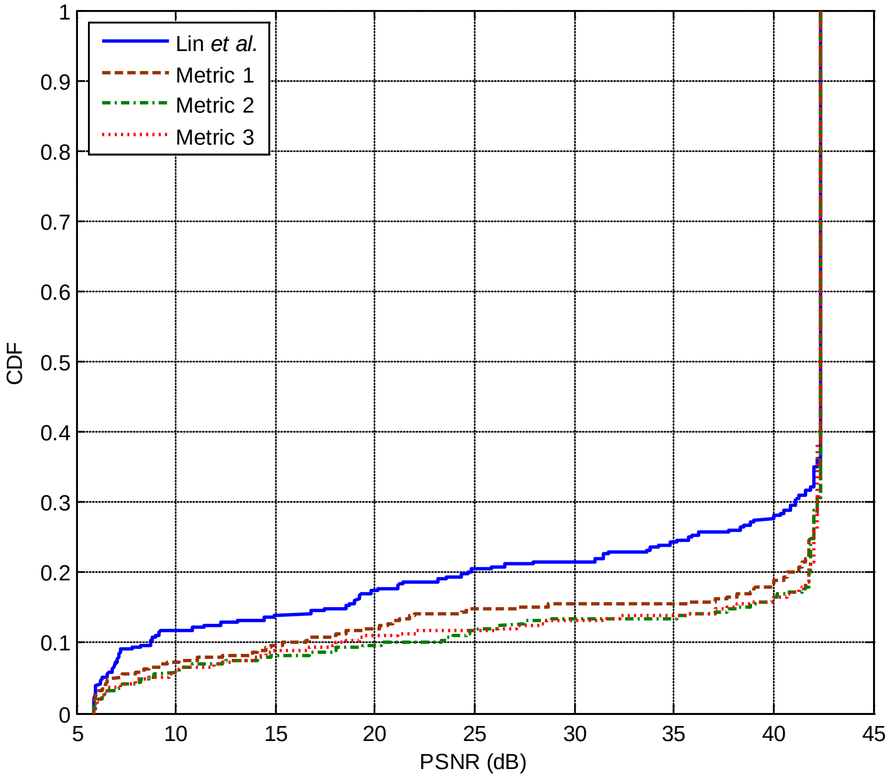

Fig. 5. CDF of node ratio with respect to the PSNR.

Finally, we evaluate the transmission performance after selecting the relays and allocating the resources to them. We assume that 30 nodes are randomly distributed in each topology. For the performance comparison, we consider an existing scheme which was proposed by Lin *et al.* [2].

Fig. 5 depicts the CDF of the number of nodes with respect to the

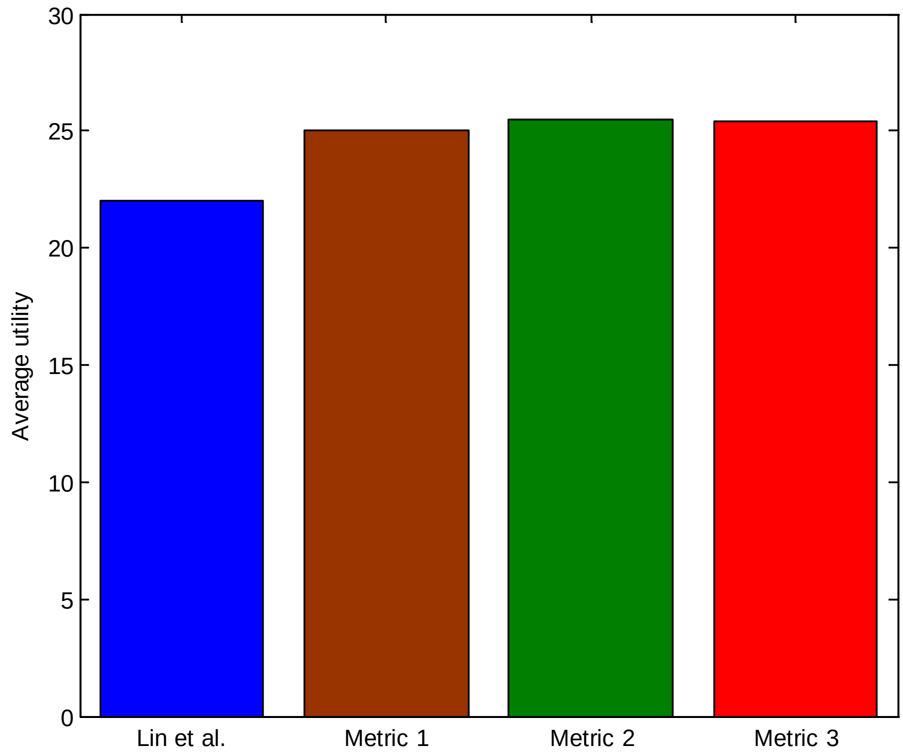

Fig. 6. Average utility of each algorithm.

peak signal to noise ratio (PSNR). We observe that the proposed algorithms perform better than the existing scheme. Especially, we focus on the 38.5 dB PSNR which is obtained when the decoding failure rate is 0.5%. In the algorithms using Lin *et al.*, Metric 1, Metric 2, and Metric 3, the node ratios satisfying the PSNR over 38.5 dB are 72.8%, 83.1%, 84.8%, and 84.5%, respectively. Therefore, the proposed algorithms

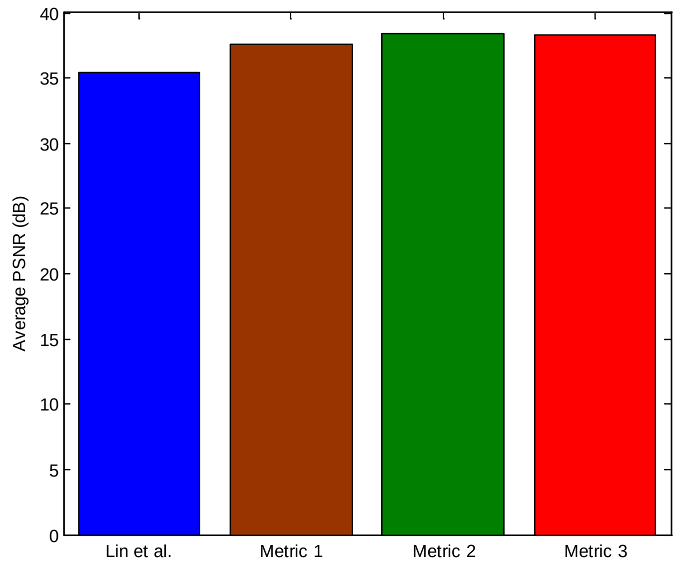

Fig. 7. Average PSNR of each algorithm.

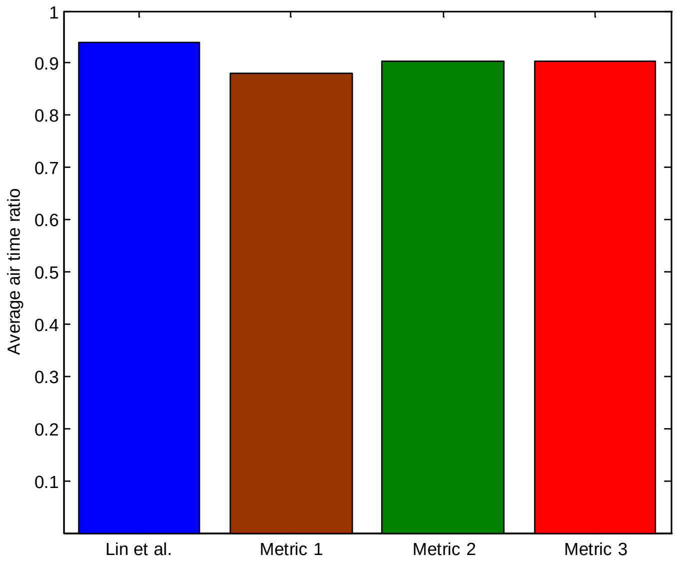

Fig. 8. Average air time ratio of each algorithm.

improve the satisfied node ratio by more than of 10% over Lin *et al.*

Fig. 6 depicts the average utilities which are the sum of the average number of nodes over 38.5 dB and average air time ratio. In Lin *et al.*, Metric 1, Metric 2, and Metric 3, the average utilities are 22.03, 24.99, 25.52, and 25.42, respectively. We observe that the proposed algorithms yield the higher average utility than the algorithm of Lin *et al.*

Fig. 7 depicts the average PSNR of each algorithm. In Lin *et al.*, Metric 1, Metric 2, and Metric 3, the average PSNRs are 35.46 dB, 37.62 dB, 38.36 dB, and 38.26 dB, respectively. Fig. 8 depicts the average air time ratio of each algorithm. In Lin *et al.*, Metric 1, Metric 2, and Metric 3, the average air time ratios are 0.94, 0.88, 0.90, and 0.90, respectively. From Figs. 7 and 8, we observe that the proposed algorithms utilize less air time while providing the higher video quality.

Chapter 6

Conclusion

The thesis has presented a new algorithm that jointly selects relays and allocates the resources by taking advantage of the RLNC-based two-hop multicast. It first formulated an optimization problem to maximize the number of decodable nodes for reliable video packet transmission and to minimize the number of total transmitted packets for bandwidth efficiency. Since the optimization problem is not convex, the problem is reformulated to an LP problem by relaxing the constraints, which turned out to be a convex problem. Based on the LP problem, heuristic algorithms are developed for selecting the relays and allocating the resources.

The proposed joint algorithm first sets the range of the number of packets transmitted from the source, and then determines the relay set and the allocated resources by using LP. Noting that the solution of the

LP is real value, the proposed algorithm is designed to transform real values to the proper integer values. In case the resources allocated for the given nodes do not meet the time constraints, the nodes are excluded until they satisfy the time constraints by using the proposed heuristic metric.

According to simulation results, the solution of the proposed algorithms turned out to be very close to the optimal solution obtained by exhaustive search. In addition, it turned out that the proposed algorithms outperform the existing scheme in terms of utility as well as PSNR and air time usage. Therefore, the proposed algorithms provide higher quality of video to the larger number of users even with less air time compared with the existing scheme.

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국문 초록

본 논문에서는 무선 랜에서 네트워크 코딩 기반의 비디오 멀티캐스트를 위한 릴레이 선택 및 자원 할당 기법을 다룬다. 무선 랜에서 그룹 안의 여러 노드들에게 동시에 실시간 비디오를 전송함에 있어서 멀티캐스트가 효과적이다. 그러나 기존의 IEEE 802.11 무선 랜 멀티캐스트 방식에서는 재전송이 없기 때문에 패킷 전송에 대한 신뢰성이 보장되지 않는다. 그러나 랜덤 선형 네트워크 코딩을 이용하여 암호화된 패킷들을 전송하면, 일부 패킷이 유실되더라도 신뢰성 있는 전송이 가능하다. 또한 릴레이를 사용하면 단일 홉으로 전송하는 것보다 대역폭 효율 면에서 더 효과적인 전송이 가능하다. 본 논문에서는 네트워크 코딩과 릴레이의 장점으로부터 우선 최대한 많은 노드에게 신뢰성 있는 전송을 보장하고 이 때 전송하는 전체 패킷의 수를 최소화하는 릴레이 선택과 자원 할당을 위한 최적화 문제를 형성하였다. 이 문제는 볼록(Convex) 문제가 아니기 때문에 풀기 어렵지만, 주어진 조건을 완화함으로써 전송 패킷의 수를 최소로 하는 선형 계획법(Linear programming)으로 변형할 수 있다. 본 논문에서는 이러한 선형 계획법을 기반으로 최적화 문제의 해를 구하기 위한 알고리즘을 제안한다. 시뮬레이션을 통해 제안된 기법의 해가 최적 기법의 해에 근접함을 보이고, 디코딩이 가능한 노드의 수와 전송 점유시간의 비교를 통해 현존하는 다른 기법보다 제안 기법이 우월하다는 것을 검증하였다.

주요어: 비디오 멀티캐스트, 랜덤 선형 네트워크 코딩, 릴레이.

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